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Experiments on Strength and Ductility Characteristics of Polypropylene Fiber-Reinforced Concrete

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Abstract: Concrete is a common material in construction which has a brittle behavior and can undergo severe structural discontinuities and crushing as a result of growth and propagation of cracks. Prior research shows that using polymer material such as polypropylene fibers can be effective in restricting crack propagation and improving the performance of the concrete. Despite the reported studies, further systematic investigations are still required to demonstrate the enhanced performance of polypropylene fiber-reinforced concrete for a variety of structural and seismic applications. On this basis, the effects of addition of polypropylene fibers on the strength and ductility performances of ordinary concrete are investigated in this research endeavor through compressive and flexural experiments. Three types of concrete are considered which include plain concrete with no added fibers and polymer concretes with 0.1% and 0.2% fibers added by weight of cement. Compressive and flexural tests are conducted on eighteen standard cylinders and six beam specimens, respectively, at ages of 7, 14, and 28 days. Quasi-static loading is applied under displacement control. This study demonstrates that the strength and ductility performances of concrete can be enhanced through proper detailing and addition of optimal amount of polypropylene fibers.
Keywords: Concrete; Polypropylene fibers; Strength; Ductility; Experimental investigation.

1. Introduction

Concrete is a composite material with significant economical, environmental, and structural advantages that is widely-used in construction. Low cost, easy access to ingredients, and corrosion as well as fire resistances are some of the factors that have enabled the common use of concrete in the construction industry [1]. Concrete cracking can occur for a variety of reasons, e.g. load, shrinkage, creep, temperature, and settlement. This behavioral weakness is often overcome by using steel rebars and composite fibers in order to connect the areas on both sides of the crack and relieve stress transfer and redistribution along the cracked concrete body. Since the use of steel reinforcement may not be possible in some cases due to, for instance, limited member dimensions and/or decreased concentration of the rebar, other forms of reinforcement with a finer texture than the rebar such as polymer fibers including aramid, Kevlar, carbon, glass, polypropylene, etc., can be considered. Addition of such fibers can ensure the homogeneity of distribution of mechanical properties in the concrete environment and also can improve ductility prior to failure. At present, polymer concretes made on this basis are widely used in road construction, airport runway paving, impact shields, impact and explosion resistant structures, dynamic machinery, etc. [2].

A literature survey reveals the advantages of use of polymer fibers in performance enhancement of concrete structures. In recent years, great research works have been performed on the properties, performance, and applications of polymer concrete. Some exemplary published research works only are cited in here for brevity. Mansour et al. [3] reported a study of a polymer concrete, made up of natural aggregates and an orthophthalic polyester binder, reinforced with natural Alfa fibers. Through flexural testing and fracture investigations, the desirable properties and high performance of this type of concrete were demonstrated. Senthamilselvi and Palanisamy [4] presented a study on the flexural behavior of reinforced fly ash (FA)-based geopolymer concrete beams with partial replacement of FA for about 10% by weight with paper sludge ash. Performance aspects, e.g. load carrying capacity, were studied and a good agreement was shown between numerical and experimental failure behaviors. Esmaeili and Andalibi [5] developed a 3D Meso-Scale finite element model to study the mechanical behavior of steel microfiber-reinforced polymer concrete. It was shown that application of microfibers with a higher aspect ratio can improve the mechanical properties of the composite considerably. Marthong [6] investigated the effect of polypropylene fibers on the mechanical strength of concrete. It was demonstrated that the use of polypropylene fibers can significantly improve the flexural and splitting tensile strengths of concrete materials. In an experimental work reported by Kar and Biswal [7], the feasibility of shear strengthening of reinforced concrete beams with Basalt fiber reinforced polymer composites was explored. The effectiveness of such a reinforcing alternative in enhancing the performance of the beams was demonstrated. Asteris et al. [8] studied the effect of the aggregate type and addition of steel fibers on the mechanical properties of polymer concrete. The effectiveness of addition of the granite and silica aggregates as well as steel fibers in improving the mechanical properties of polymer concrete was shown. Akbar et al. [9] reported a study on the use of waste material such as bagasse ash (geopolymer) to reduce cement production and improve its physical properties in a sustainable way. The feasibility of bagasse ash geopolymer incorporating propylene fibers to enhance mortar strength was evaluated. It was shown that limiting the content of propylene fibers to 1%, not only improves the flexural properties but also enhances the compressive strength by providing denser microstructure. Liu et al. [10] summarized the influence of polypropylene fibre on the durability of concrete, including drying shrinkage, creep, water absorption, permeability resistance, chloride ion penetration resistance, sulfate corrosion resistance, freeze-thaw cycle resistance, carbonation resistance, and fire resistance. The benefits of Polypropylene fiber in enhancing the durability of concrete were discussed. Blazy and Blazy [11] conducted a research to study and sum up the influence of polypropylene fibers on the physical and mechanical properties of concrete and to discuss how polypropylene fiber reinforced concrete can be used in a promising field of application which are public spaces. It was proved that public spaces are a promising field of polypropylene fiber reinforced concrete application, since they are subjected to unfavorable environmental conditions, impact damages, surface abrasion, and vandalism. Zhou et al. [12] applied the discrete element method for predicting the tensile properties of polypropylene fiber-reinforced concrete. The results revealed the effectiveness of the proposed model in predicting the splitting tensile responses of polypropylene fiber-reinforced concrete. In another recently-reported study, Pham et al. [13] showed that the addition of polypropylene micro-fibers significantly improves the impact behavior of fiber-reinforced ultra-high-performance concrete columns by shifting the failure mechanism from brittle shear to favorable flexural failure. The crack-control capabilities of polypropylene fiber in reinforced concrete beams have also been highlighted in recent studies [14].

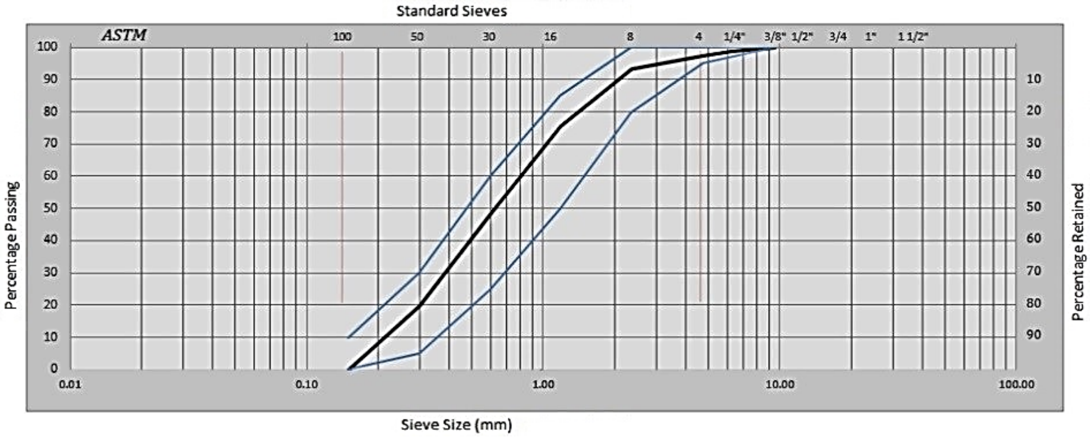
On the basis of a comprehensive literature survey and with the aim of addressing the current research needs, this study intends to investigate the strength and ductility performances of a polymer concrete produced by addition of polypropylene fibers with different mixing rates though compressive and bending experiments. Polypropylene is by and large an affordable fiber, which is easily implemented and compatible with most cement-based materials, and hence a popular choice for large-scale construction projects. These fibers are believed to have a good bond with concrete and provide a better distribution of deformation throughout the concrete environment in order to prevent the concentration of cracks and local fractures; however, in order for economical and widespread application of such polymer fibers, particularly in the design and construction of earthquake-resistant structures, further detailed and systematic investigations are required. To this end, the compressive and flexural performances of several concrete specimens with different percentages of polypropylene fibers at different ages are compared with those of the fiber-free control concrete specimens and assessments are made on the structural application of such polymer fibers.

2. Fabrication of concrete test specimens

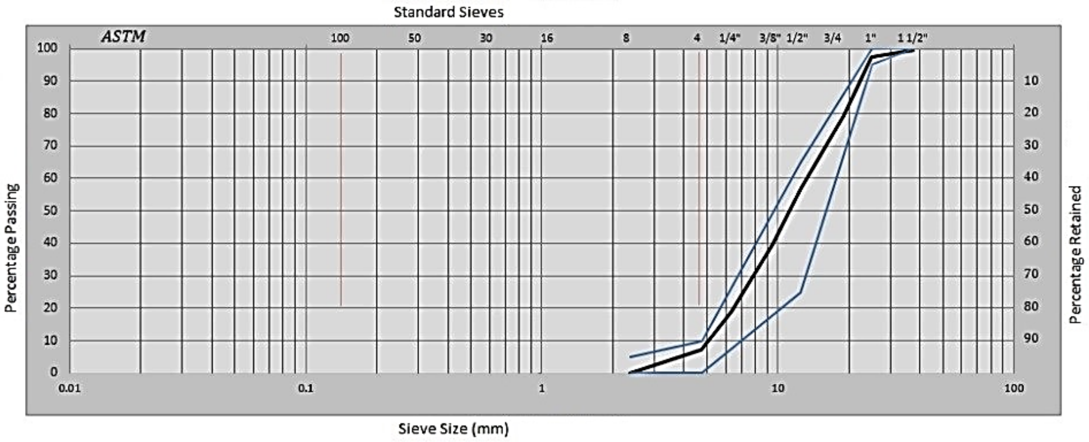
Sieve analysis was one of the very first tests performed to evaluate the gradation of the granular materials and to select the appropriate aggregates for the concrete mix. The sand and gravel distribution curves obtained for the gradation tests are shown in Fig. 1. Portland Type 1 cement was utilized. A concrete mix design was carried out to select suitable ingredients of concrete, i.e. cement, water, fine aggregate (sand), and coarse aggregate (gravel), and to determine the relative proportions in order to meet the required strength and durability requirements. Table 1 summarizes the amounts of the mixture ingredients for production of 1.0 m^3 concrete with a design strength of 25 MPa, determined according to the ACI code [15].

In order to prepare the polymer concrete, the aggregate materials were initially mixed for 2 minutes by means of a mechanical mixer and during this process, half of the design water was added to the mixture. Subsequently, the cement was added and mixing was performed for another minute. Considering the selected concrete slump, i.e. 100 mm, the remaining water and the dry polypropylene fibers were then added to the mixture and mixing was continued for 3 more minutes. The concrete was poured into the standard cylindrical as well as cuboid molds and compacted using a vibratory table. The molds were completely covered with a damp sack for one day and opened after setting. The hardened samples were transferred to a curing pond and stored at a constant temperature of 15°C until the age of the test sample (see Fig. 2). Some fabricated compressive and flexural specimens are shown in Fig. 3.

It is noted that dry fibers were added during the mixing process in order to maintain the cohesion of the polymer concrete structure. Polypropylene fibers were corrugated yarns with an average length of 10 mm which were produced by the BASF German company (see Fig. 4). In order to prevent the accumulation of fibers and their pellets, which often occurs due to insufficient performance of concrete during its production, the amount of water required to simultaneously maintain the strength of concrete and achieve the complete mixing of fibers was initially estimated through the design reference regulations and then adjusted while making the concrete.



(a) Fine aggregates



(b) Coarse aggregates

Fig. 1. Granulation curves for sand and gravel

Table 1. Specifications and amounts of concrete ingredients (vol.: 1.0 m^3; strength: 25 MPa)

W/C ratio	Water	Cement	Sand	Gravel
0.45	135 gr.	300 gr.	1170 gr.	780 gr.

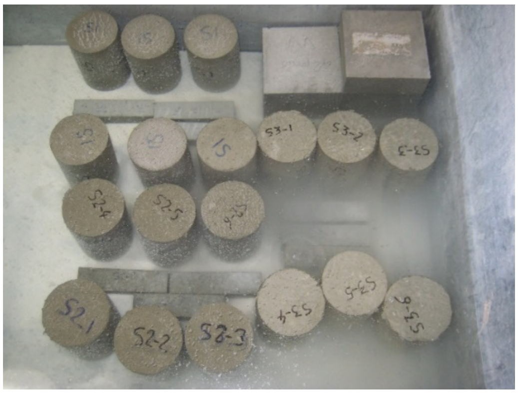


Fig. 2. Test specimens in the curing pond

Fig. 3. Fabricated cylindrical and cuboid test specimens

Fig. 4. Used polypropylene fibers

3. Compressive and flexural tests

In this research endeavor, cylindrical specimens with a diameter of 100 mm and a height of 200 mm were tested under uniaxial pressure (see Fig. 5) in accordance with the ASTM C39 standard [16] and three-point bending tests were conducted on 160 mm long cuboid beams with 40 mm width and height under uniform static loading (see Fig. 6) in accordance with the ASTM C78 standard [17]. Plain and fiber-reinforced concrete specimens were fabricated and tested in order to investigate the effectiveness of the added fibers and also the performance of the polymer concrete. Reinforced concrete specimens were fabricated through the addition of 0.1% and 0.2% fibers by weight ratio of cement. These percentages were selected by taking into account the standard polypropylene-addition range on the basis of strength, durability, workability, etc. considerations. The cylindrical specimens were tested at the ages of 7, 14, and 28 days. The compressive tests were conducted under displacement control and the axial stress and strain were measured and monitored simultaneously. The cuboid beam specimens were tested only at the age of 28 days. The experimental program included the testing of eighteen cylindrical and six cuboid beam specimens whose specifications are summarized in Table 2.

Fig. 5. Cylindrical test specimen under uniaxial pressure

Fig. 6. Three-point flexural testing of a concrete specimen

Table 2. Specifications of the tests and specimens

Test (specimen)	Concrete	Age (days)	No. of specimens	Total no. of specimens
Compressive (cylinder)	Plain (no fiber)	7,14,28	6	18
	Polymer (0.1% fiber)	7,14,28	6	
	Polymer (0.2% fiber)	7,14,28	6	
Flexural (cuboid beam)	Plain (no fiber)	28	2	6
	Polymer (0.1% fiber)	28	2	
	Polymer (0.2% fiber)	28	2	

In order to standardize the sensitivity of the behavior to the cement grade, the strength of the design concrete was considered to be 25 MPa. Also, in order to provide the desired concrete density and fiber adhesion, the maximum diameter of the largest aggregate, i.e. 10 mm, was taken into consideration. The compressive and bending loads were applied at a rate of 0.5 MPa per second and 0.01 MPa per minute (at compression area of the beam), respectively, according to the relevant standards. Moreover, the average duration of each experiment was 3.5 minutes. Figs. 7 and 8 show the rupture of the compressive and flexural specimens, respectively.

Fig. 7. Crushing patterns in specimens under compressive test

Fig. 8. Failure at midspan of a specimen under flexural test

4. Discussion of results

The results of compressive tests of the plain and polymer concretes with different fiber ratios at different ages are shown in Fig. 9. From the figure, it is evident that addition of polypropylene fibers up to 0.1% resulted in increasing of the compressive strength by 10% at the age of 7 days, while further increasing of the fibers up to 0.2% resulted in 8% decrease in strength compared to the control specimen made of plain concrete. At the age of 14 days, inclusion of the polypropylene fibers up to 0.1% and 0.2% resulted in respective increasing and decreasing of the compressive strength by 6% and 10%. Lastly at the age of 28 days, the compressive strength of the polymer concrete with 0.1% fiber was not changed, while a 9% decrease in strength was observed due to addition of 0.2% fibers compared to the control specimen.

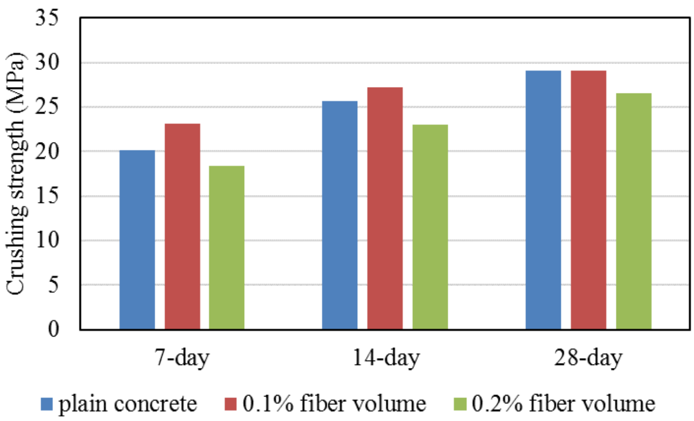
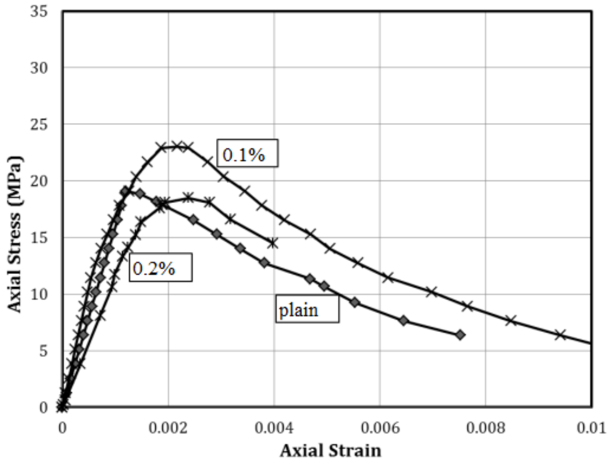


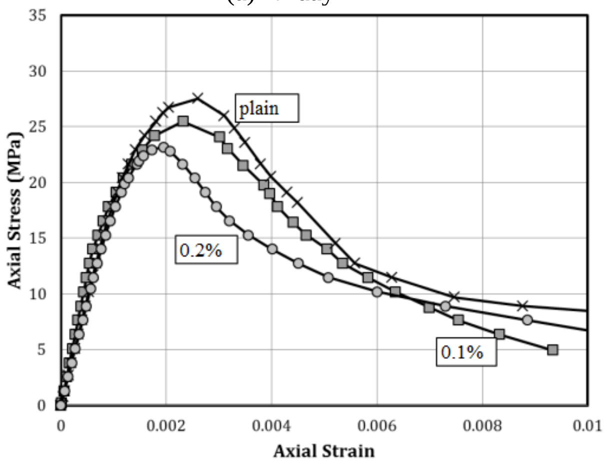
Fig. 9. Crushing strengths of 7-, 14-, and 28-day plain and fiber-reinforced concretes

The axial stress-strain plots for the 7-, 14-, and 28-day plain and fiber-reinforced concretes subjected to compressive load are shown in Fig. 10. Consistent with all the investigated cases in this figure, the stress-strain plot shows an increasing trend at the initial stages of loading up to a peak and then starts to decay slowly. The strains corresponding to the maximum stresses are found to be in the range of 0.001-0.003. From Fig. 10, addition of 0.1% fibers is found to be by and large effective in enhancing the material properties of concrete, while addition of further fibers up to 0.2% has not been efficacious in improving the stiffness as well as strength performances of concrete.

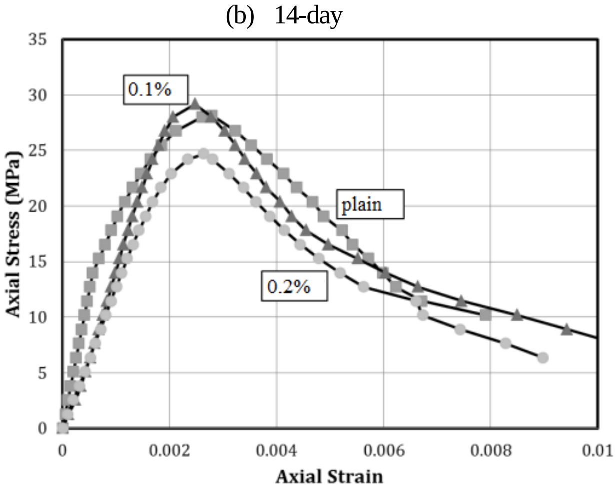
It is noted that, in general, polypropylene polymers have a palpable effect on concrete strength before its complete hardening and this effect tends to diminish over time. In other words, the effectiveness of addition of a specific amount of polymers in increasing the compressive strength of concrete declines as the concrete gets aged. Also, this study shows that when the amount of the added polypropylene surpasses the optimum limit of 0.1%, the ductility of the concrete mixture improves remarkably. The compressive crushing strains of the 7-, 14-, and 28-day plain and fiber-reinforced concretes are shown in Fig. 11.



(a) 7-day



(b) 14-day



(c) 28-day

Fig. 10. Stress-strain plots for plain and fiber-reinforced concretes

The compressive test results depicted in Fig. 11 demonstrate that despite the negative effect of addition of 0.2% polypropylene fibers on the compressive strength as shown in Figs. 9 and 10, addition of polypropylene fibers beyond 0.1% enhances the ductility of the concrete significantly. Quantitatively, polymer concretes with 0.1% and 0.2% fibers possess 10% and 13% increase in ductility, respectively, compared to control concrete at 7 days of age. At the age of 14 days, the ductility of the polymer concretes is increased by respective 20% and 34%. Lastly, 28-day concrete with 0.1% and 0.2% fibers possesses 31% and 48% increase in ductility, respectively, compared to the corresponding control concrete.

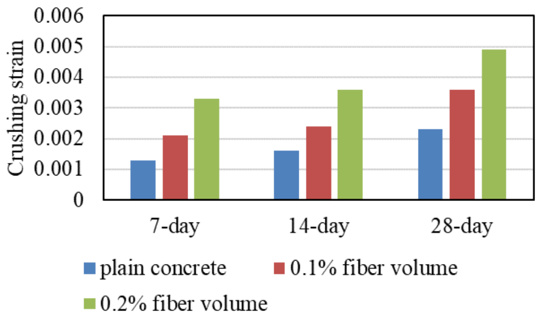


Fig. 11. Crushing strains of 7-, 14-, and 28-day plain and fiber-reinforced concretes

The load-midspan deflection responses of the beam specimens obtained from the flexural testing of the plain and polymer concretes are shown in Fig. 12. These results indicate a 20% increase in flexural strength of the beam with 0.1% fibers compared to the one made of plain concrete. Nevertheless, the specimen made of polymer concrete with 0.2% fibers experiences a 10% reduction in its flexural strength. Also, assessment of deformation of the beams before failure reveals 30% and 25% increase in the ductility of the specimens with 0.1% and 0.2% fibers relative to the beam made of plain concrete. This is indicative of ductile behavior of the beam specimens made of polymer concrete.

Based on the results and findings of this research, it can be concluded that addition of 0.1% polypropylene fibers can increase both strength and ductility of concrete. Further addition of fibers beyond the optimal limit of 0.1% will result in improvement of ductility and degradation of strength. It is noted that the addition of the *optimal* amount of fibers is important in effective enhancement of the performance as shown in another study on the impact-resistance improvement of concrete slabs reported by Al-Rousan et al. [18]. It is also noteworthy that the fiber reinforcement is effective in controlling the crack mechanisms of concrete and overcoming its brittleness issue [19]. Overall, addition of polypropylene fibers in production of polymer concrete with enhanced strength and ductility performances is found to be promising. These findings can be utilized in the design of concrete structures with desirable structural and seismic performances.

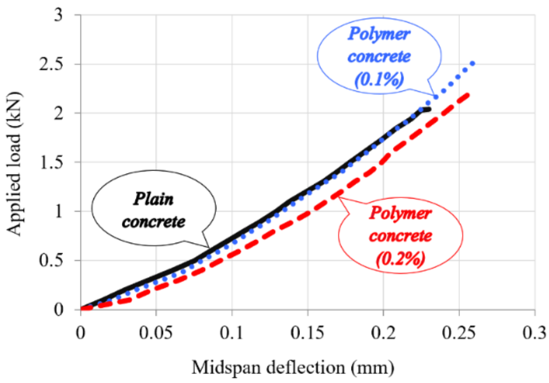


Fig. 12. Load-midspan deflection responses of beam specimens

5. Conclusion

In this research, the effects of addition of polypropylene fibers for production of polymer concrete with enhanced strength and ductility performances were investigated experimentally by conducting compressive and flexural tests on 18 cylindrical and 6 beam specimens, respectively. Compressive and flexural experiments were carried out on control (with no fibers) and polymer (with 0.1% and 0.2% fibers by weight of cement) concretes.

It was shown that addition of 0.1% fibers can increase the compressive or crushing strength of concrete, while addition of further fibers beyond the optimum limit of 0.1% can adversely affect the strength performance of concrete. Similarly, the flexural strength of polymer concrete with a fiber content of 0.1% is improved compared to that of the plain concrete, while addition of 0.2% fibers reduces the flexural strength of the concrete. In all, compressive and flexural tests demonstrated that the strength performance of concrete can be improved due to addition of 0.1% fibers and addition of further fibers beyond this amount can lower its strength performance.

Furthermore, it was found that the crushing strain of concrete under compressive loading increases remarkably as a result of addition of 0.1% and even 0.2% polypropylene fibers. Similarly, addition of 0.1% and 0.2% fibers significantly improves the flexural ductility of the concrete compared to that of the plain concrete. Overall, based on the findings from the compressive and flexural experiments, ductility of concrete is improved due to addition of polypropylene fibers regardless of amount of the added fibers.

Addition of polypropylene fibers is shown to be by and large effective in improving the strength and ductility performances of concrete. On this basis, production and application of such a polymer concrete as a sustainable building material is found to be promising in design of high-performing and resilient structures. In particular, enhanced concrete strength and ductility performances can improve the structural and seismic performances of buildings.

6. References

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